



---

# **Micro Weather Station for In Situ Atmospheric Measurements in the Troposphere**

Greg Cardell, Flavio Noca, Kevin Watson and Michael Hoenk

In Situ Exploration Technology Group  
Device Research and Applications Section  
Jet Propulsion Laboratory  
California Institute of Technology

This work was carried out by the Center for Space Microelectronics at NASA's Jet Propulsion Laboratory, California Institute of Technology, under contracts with the National Aeronautics and Space Administration:

Earth Science Enterprise -- Atmospheric Dynamics and Radiation Program  
Space Science Enterprise --  
HEDS Enterprise -- Advanced Environmental Monitoring Program  
JPL/Caltech -- DRDF, PF

The NASA Atmospheric Dynamics and Radiation Program is gratefully acknowledged for initial and continued support of this work.



# The JPL Surface Acoustic Wave Hygrometer

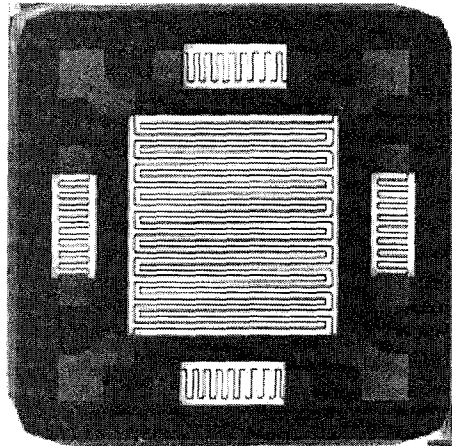


## Motivation:

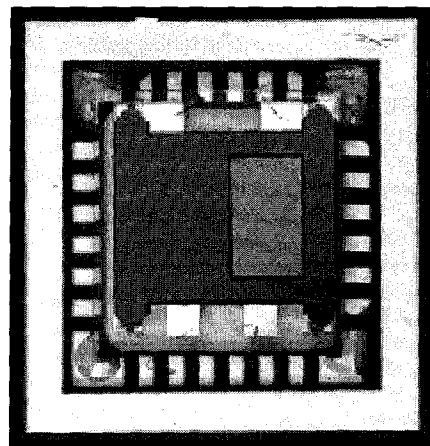
The JPL SAW Hygrometer was developed as part of an overall miniature instrument development effort. The original goal was a Microweather Station for deployment to the surface of Mars.

The development of several sensors was initiated, including MEMS temperature, pressure and wind sensors

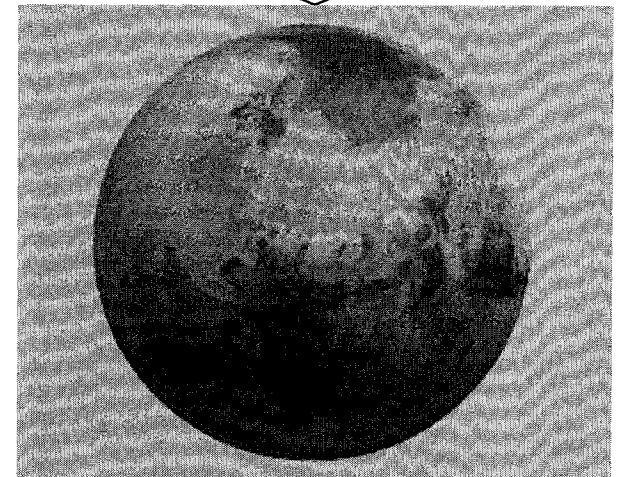
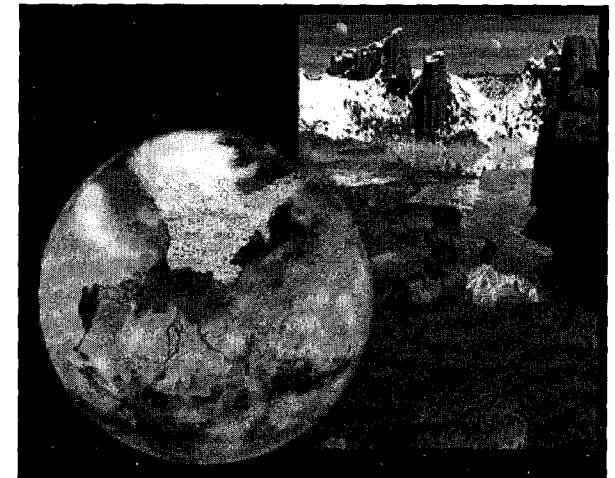
Thermal Wind Sensor



Pressure Sensor



Of these, all except wind and humidity sensors have been superseded by COTS products.





# The JPL Surface Acoustic Wave Hygrometer



What's a hygrometer, anyway? Why measure humidity?

A *hygrometer* is an instrument for measuring humidity in the atmosphere

## Atmospheric Dynamics: Weather

The latent heat of vaporisation of water (released when liquid changes to vapor, absorbed when vapor condenses) is  $2.50 \times 10^6 \text{ J / kg}$ . This is a lot of energy.

Owing to its involvement in radiative processes, cloud formation, and in exchanges of energy with the oceans, water vapor is the single most important trace species in the atmosphere.<sup>†</sup>

## Planetary Science: Mars and Venus

Water is a key substance in *biology*, *climatology* and *geology* (e.g., without H<sub>2</sub>O Earth probably would not have plate tectonics<sup>‡</sup>, and Venus does not -- we don't know about Mars, yet.)

For Mars, the history of water is currently **the** fundamental science question.

## Process control:

Water is ubiquitous, an almost universal solvent, and plays a role as a contaminant or as a controlled variable in industrial processes

<sup>†</sup>*Fundamentals of Atmospheric Physics*, M. Salby, 1996, Academic Press

<sup>‡</sup>"Generation of plate tectonics from lithosphere-mantle flow and void-volatile self-lubrication"  
Bercovici D *Earth and Planetary Science Letters* **154** pp. 139-151 JAN 1998



# The JPL Surface Acoustic Wave Hygrometer



## Measures of humidity

Dewpoint: For a given pressure, *dewpoint* is the temperature at which vapor and liquid phases of water are in thermodynamic equilibrium, *i.e.*, the rate at which water evaporates is equal to the rate at which it condenses.

Absolute humidity: The mass of water vapor (per unit volume) in the air. This is just the density:

$$\rho_v = 1/v_v$$

Mixing ratio: The ratio of the total mass of water vapor to the total mass of the dry air:

$$r = \frac{m_{H_2O}}{m_{dry\ air}} = \frac{\rho_{H_2O}}{\rho_{dry\ air}}$$

Relative humidity: The ratio of the ambient vapor pressure to the saturation vapor pressure at the ambient temperature:

$$RH = \frac{p_{H_2O}}{p_{SAT}(T)}$$



# Humidity Measurement Technologies



<u>Technique</u>	<u>Comments</u>
• Gravimetric	NIST standard
• Electrolytic <ul style="list-style-type: none"><li>– Saturated salt (<i>e.g.</i>, <i>LiCl</i>)</li><li>– Electrolysis (<i>P<sub>2</sub>O<sub>5</sub></i>)</li></ul>	Older technology used in radiosondes
• Hygroscopic ( <i>e.g.</i> , <i>hygristor</i> , <i>humicap</i> )	Most widely used technology - low cost, currently used in radiosondes
• Capacitive ( <i>Al<sub>2</sub>O<sub>3</sub></i> )	Moderate cost, large range - damaged by high humidity
• Psychrometer	Primary measurement - limited dynamic range
• Dewpoint ( <i>e.g.</i> , <i>chilled mirror</i> )	Widely used where accuracy and wide dynamic range are important
• Optical <ul style="list-style-type: none"><li>– UV (<i>e.g.</i>, <i>Lyman alpha hygrometer</i>)</li><li>– Infrared (<i>e.g.</i>, <i>TDL hygrometer</i>)</li></ul>	Fast, sensitive, accurate - often used in research aircraft
• Remote Sensing <ul style="list-style-type: none"><li>– RF radiometers</li><li>– DIAL LIDAR</li><li>– GPS occultation</li></ul>	Important for global coverage - requires ground truth validation / calibration



# Relative Humidity Measurement



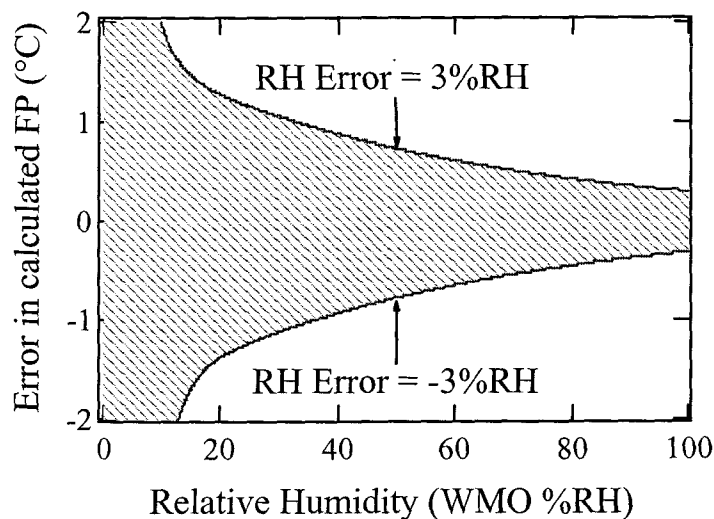
## Principle:

Material property (e.g., resistance) calibrated with respect to relative humidity (RH).

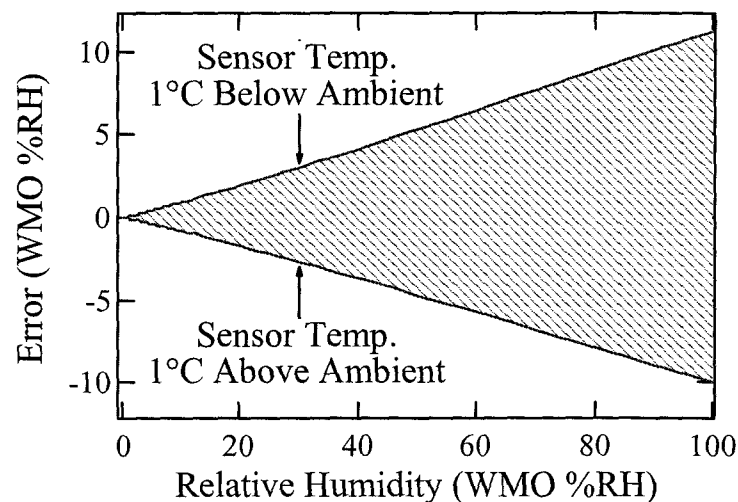
## Problems

- Calibration error
- Hysteresis and drift
- Poor response at low and high RH
- Sensitive to temperature

Uncertainty in Relative Humidity  
Effect on Calculated Frostpoint  
(at  $T_{\text{amb}} = 250 \text{ K}$ )



Uncertainty in Sensor Temperature  
Effect on Measured RH  
(at  $FP = -40^{\circ}\text{C}$ )



*Examples: Carbon Hygristor, Vaisala Humicap*

*Hygroscopic techniques measure relative humidity*



# Chilled Mirror Hygrometer



## Principle:

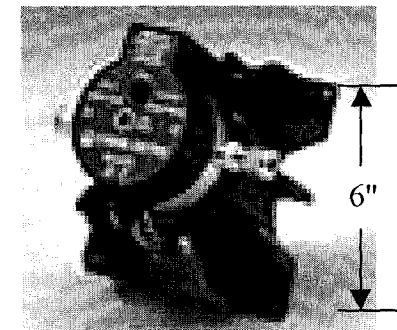
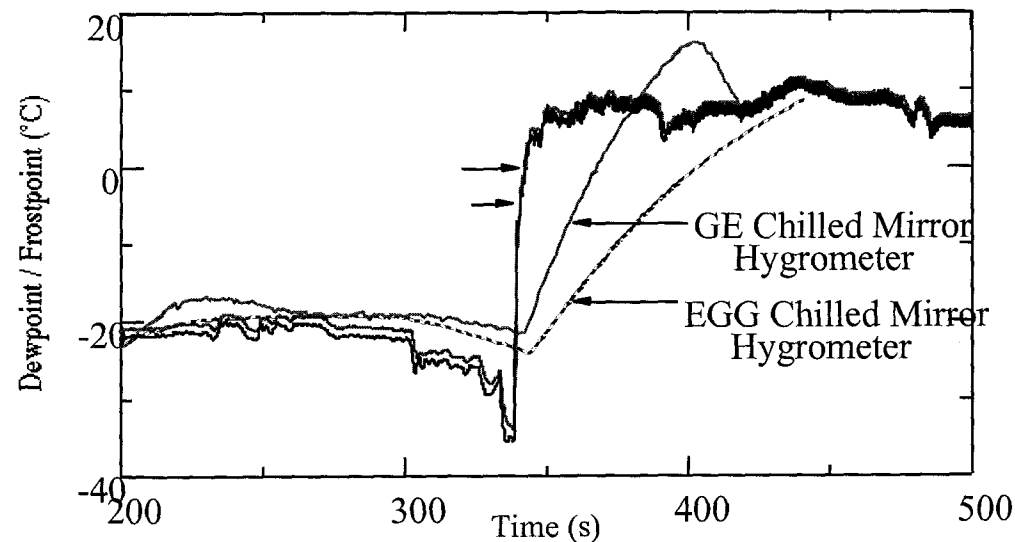
Chill a mirror until water condenses on the surface. Determine this from the reflective properties of the surface.

This is the standard dewpoint measurement instrument

## Problems

- Usually (but not inherently) big, therefore, slow
- Commercial systems have problems with loss of control tracking during large humidity changes: long reacquisition time

Humidity Measurements on NASA DC8 During Descent, 5/19/95



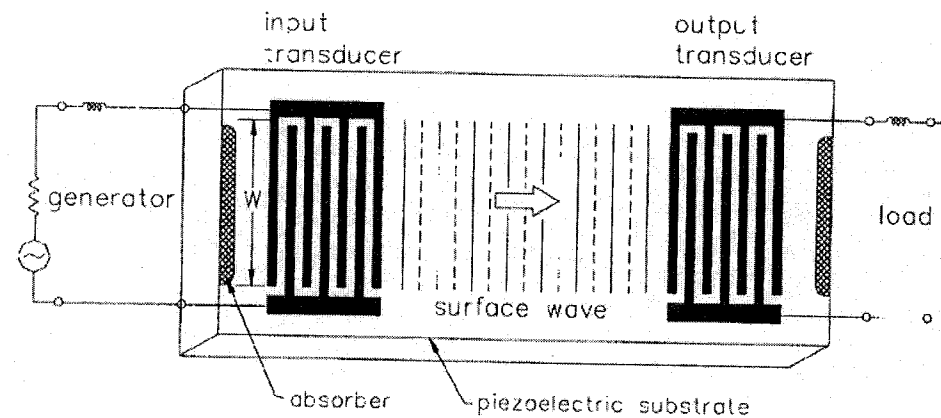
General Eastern D2 Chilled Mirror Sensor, with Two-stage TEC Capable of -40°C dewpoint



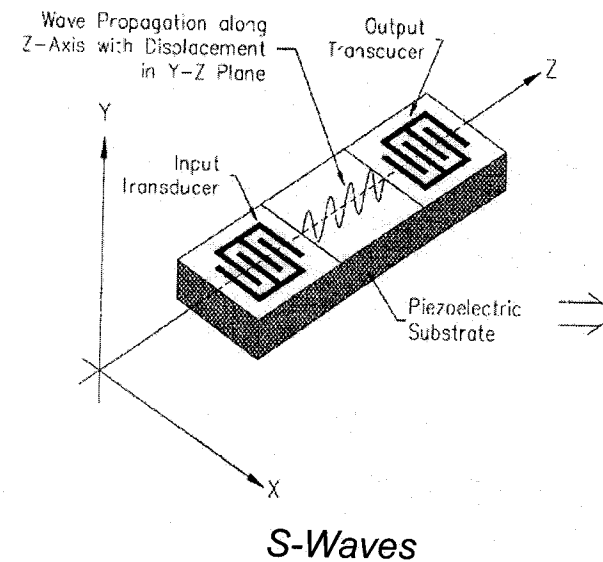
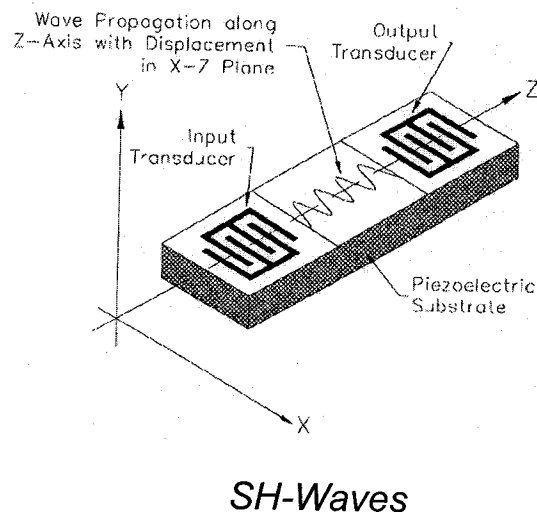
# Surface Acoustic Wave Devices



## Surface Acoustic Wave Device: Simplified diagram



## Surface acoustic waves





# Surface Acoustic Wave Devices



## Some piezoelectric materials used for SAW devices

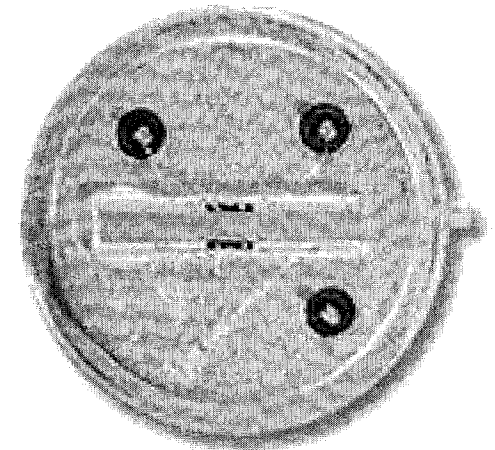
Material	Orientation	Velocity (m/s)	Temperature Coefficient (ppm/°C)	Attenuation at 1 GHz (dB/uS)	Cost
Quartz	Y, X	3159	-24	2.6	Lowest
Quartz	St, X	3158	0	3.1	Lowest
Lithium Tantalate	Y, Z	3230	35	1.14	Medium
Lithium Tantalate	167° rotation	3394	64	-	Medium
Lithium Niobate	Y, Z	3488	94	1.07	High
Lithium Niobate	128° rotation	3992	75	-	High

## SAW Applications I:

Available in wide frequency range: 30MHz to 3GHz  
High Q oscillator  
RF / IF bandpass filters in cell phones, etc.

This is a *big* market

SAW devices are manufactured by many global electronics producers: Mitsubishi, Epson, Panasonic, Toshiba



Packaged SAW



# SAW Sensors



---

## SAW Applications: Sensors

Surface acoustic waves propagate in only the top few nanometers:  
the bulk material is not affected

Sensitive to anything that changes the material properties

- Torque
- Temperature
- *Stress: surface loading*

SAW sensor operation: Embed the SAW device in a resonant circuit  
and detect changes in the resonance

## Mass detection

Minute changes in surface loading cause detectable changes in the SAW properties, analogous to a mass on a spring (sort of):

In particular, if the SAW is part of an oscillator or filter  
 *$Q$ ,  $f$  change due to loading*

All that is needed is a technique to preferentially load the SAW surface with the substance to be detected



# SAW Sensors



---

## SAW Sensor techniques: Absorption

### Preferential absorption:

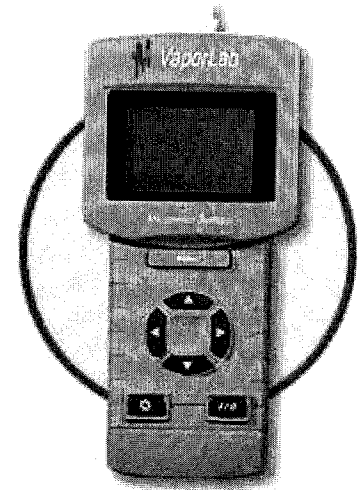
- Coat with preferential absorber
- Calibrate coated SAW (e.g., f vs. T)
- Expose to measured environment
- Treat (heat / solvents) to restore

### Problems / Challenges

- Hysteresis
- Limited life
- Contaminants

Such systems exist and have been commercialized

*Such a device can be used as an RH sensor*



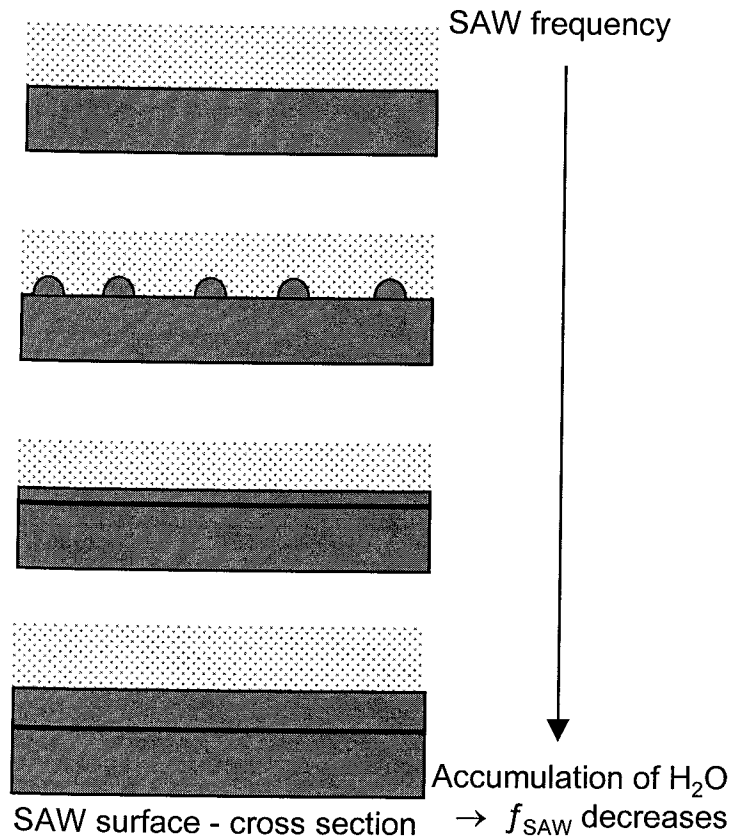
Microsensor Systems  
Vaporlab™, a hand-held, battery  
powered SAW based chemical  
vapor identification instrument



# SAW Hygrometer



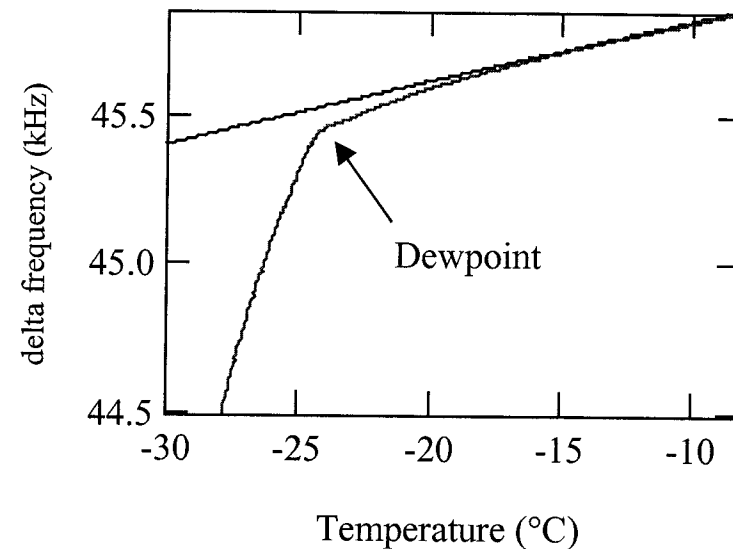
## SAW Sensor techniques: Temperature-controlled deposition (condensation)



This technique is used by the JPL SAW Hygrometer (and others)

- Calibrate dry (e.g., 99.999% N<sub>2</sub>,  $f$  vs.  $T$ , the *dry curve*)
- Expose to atmosphere
- Cool until  $|f_{wet}(T) - f_{dry}(T)| = \epsilon$
- Measure of *dewpoint* temperature → condensation temperature
- Obvious problem: At *dewpoint*, material continually accretes

**SAW Response to ramp cooling:**





# Practical SAW Hygrometry



## Algorithm:

- Choose a mass loading point:  $\Delta f = |f_{\text{wet}} - f_{\text{dry}}|$
- Maintain constant mass loading when the conditions change by holding  $\Delta f$  constant
- Closed-loop control of  $\Delta f$  using temperature

## IS THIS DEWPOINT?

### Assumptions:

Local equilibrium between liquid/vapor is possible

Equilibrium is not effected by boundary conditions, amount of condensate

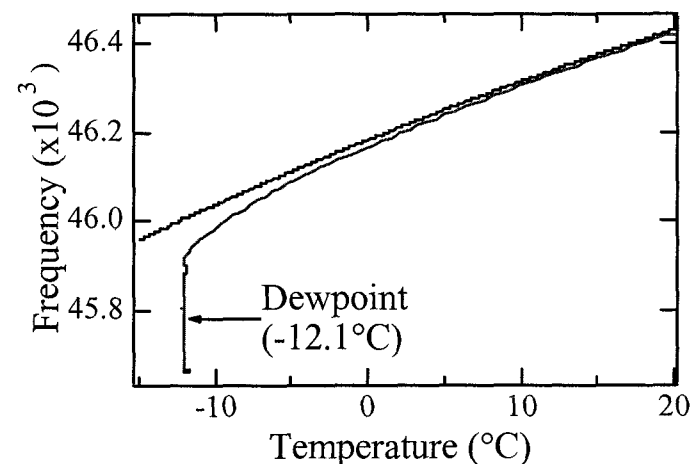
*These issues exist for all dewpoint sensors*

The choice of  $\Delta f$  is (somewhat) arbitrary:

If the sensor response is sufficiently fast, the surface temperature will track the condensation point on average for any practical value of  $\Delta f$

*Measurement is more robust than any RH sensor*

### SAW closed loop response





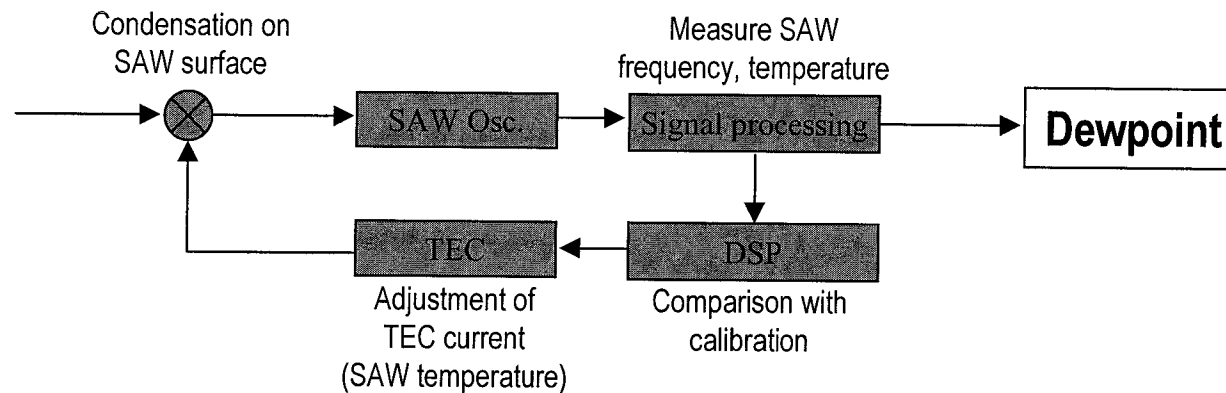
# The JPL SAW Hygrometer



## Operational considerations

There is no physical model for this system, so it is necessary to use a general purpose feedback technique: Lag-Lead control

Frequency is controlled by adjustment of TEC drive current





# SAW Hygrometer: Challenges



## *Sensor*

Sensors are fragile

- Bond wires exposed to environment
- Passivation is prone to mechanical damage
- Difficult to remove contamination (e.g. NaCl)

Each sensor must be calibrated

- $f_{\text{dry}}(T)$ , frequency reference

## *Electronics*

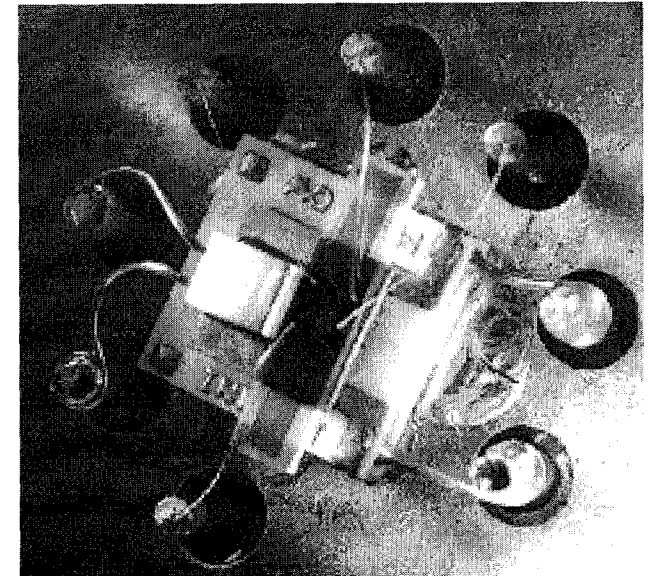
Cost

- Electronics overkill in JPL prototype
- Control algorithm is fragile and *ad hoc*

## *Methodology*

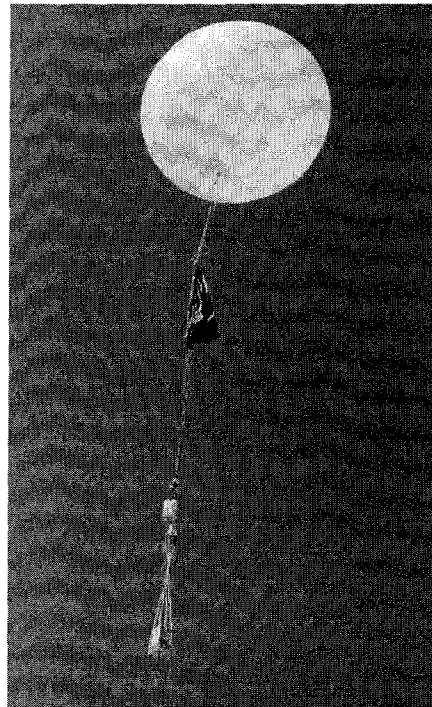
Frost / dew differentiation

SAW sensor and PRT mounted on two stage TEC, TO-3 package

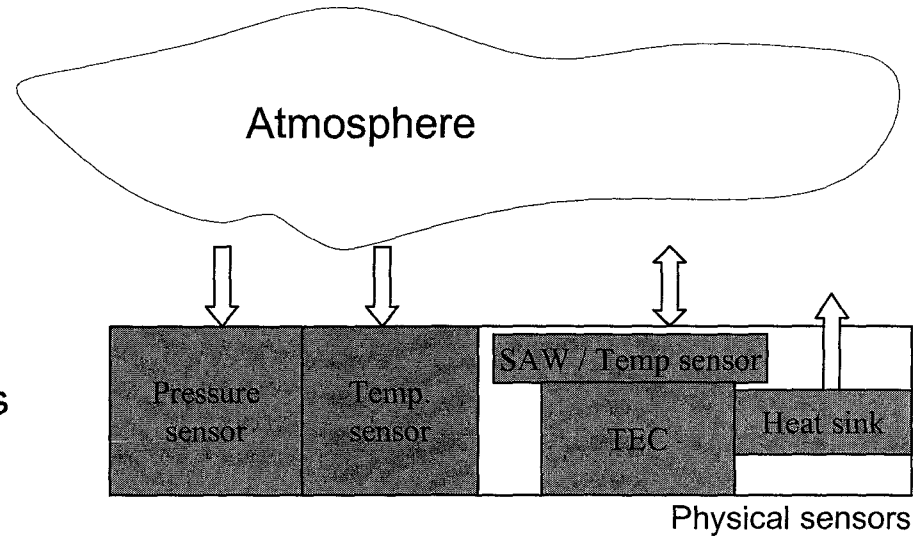




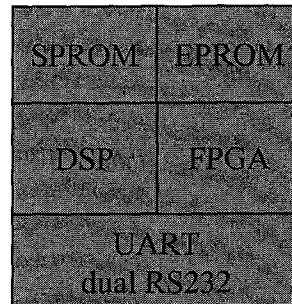
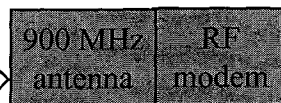
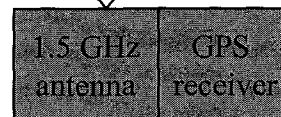
# The JPL Reference Radiosonde



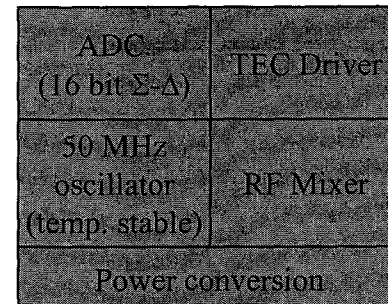
GPS  
satellites



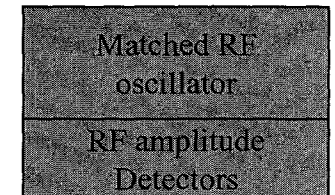
Physical sensors



Digital Electronics



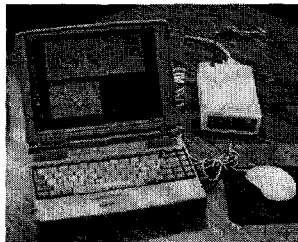
Analog electronics



RF electronics



Batteries

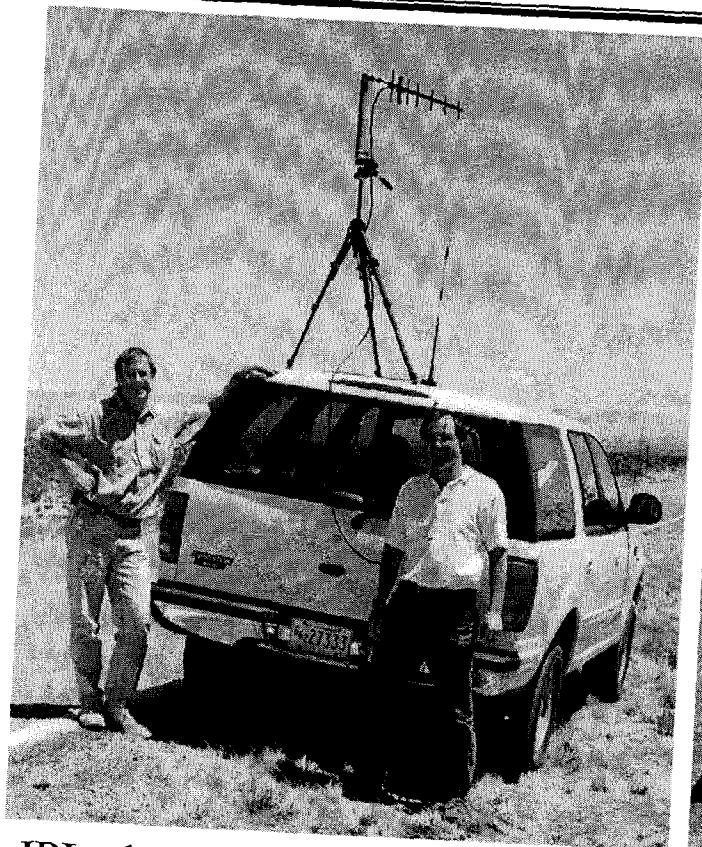


Ground  
station



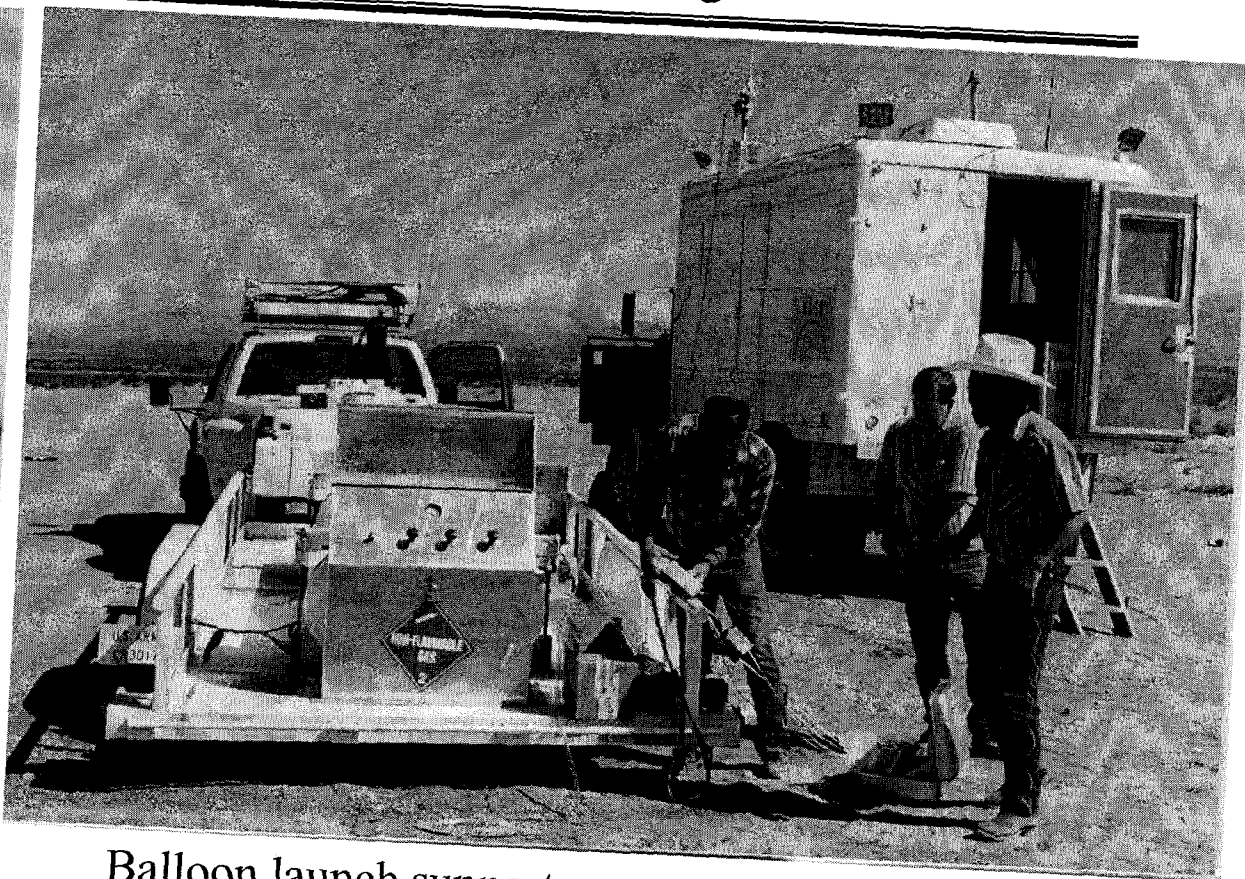
## Ground Support for Balloon Flight

JPL



JPL chase vehicle / ground station

- Laptop computer - modem
  - Remote command / control
  - Data recording
  - Real-time tracking
- GPS receiver
- Battery power

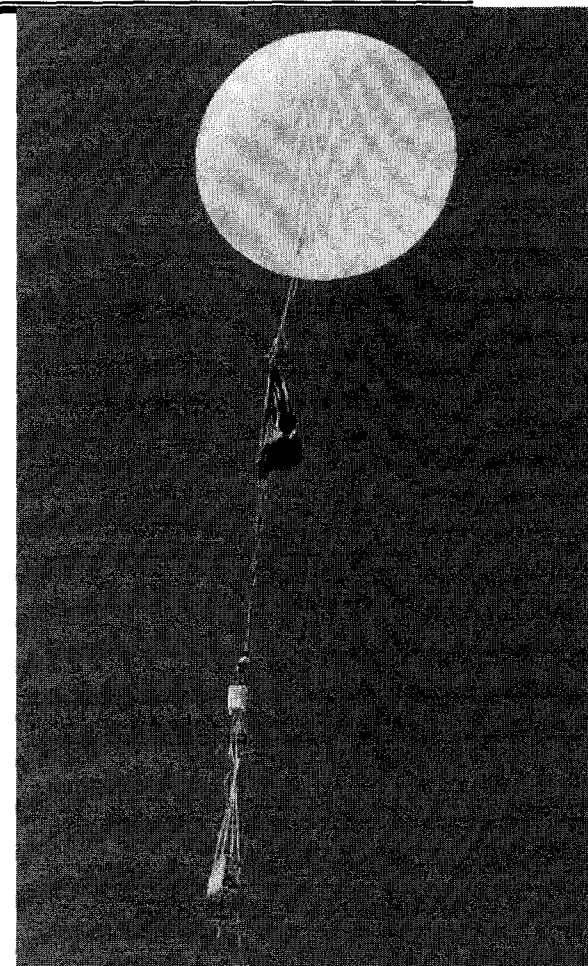
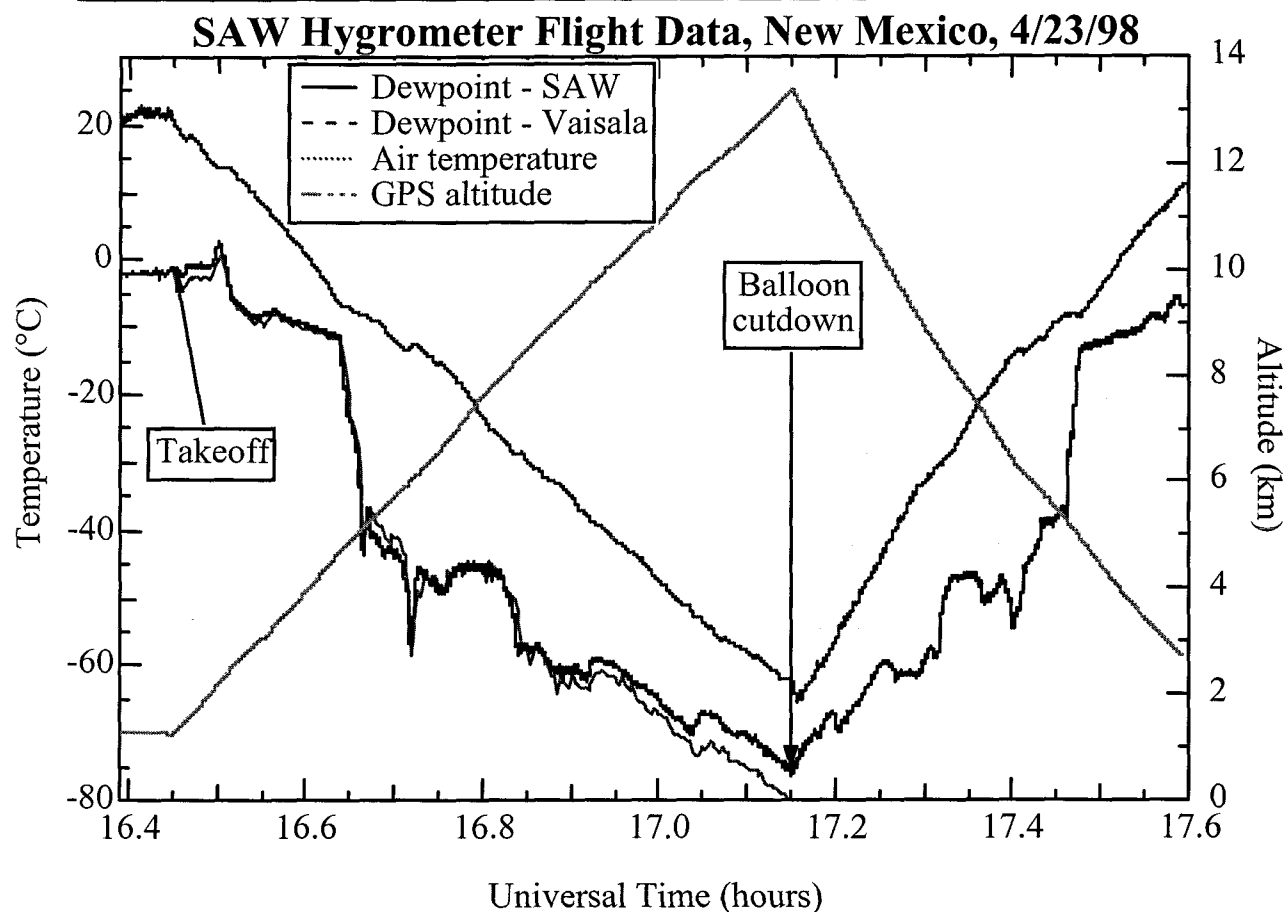


Balloon launch support

- Vaisala radiosonde ground station
- Helium tanks
- Diesel generator



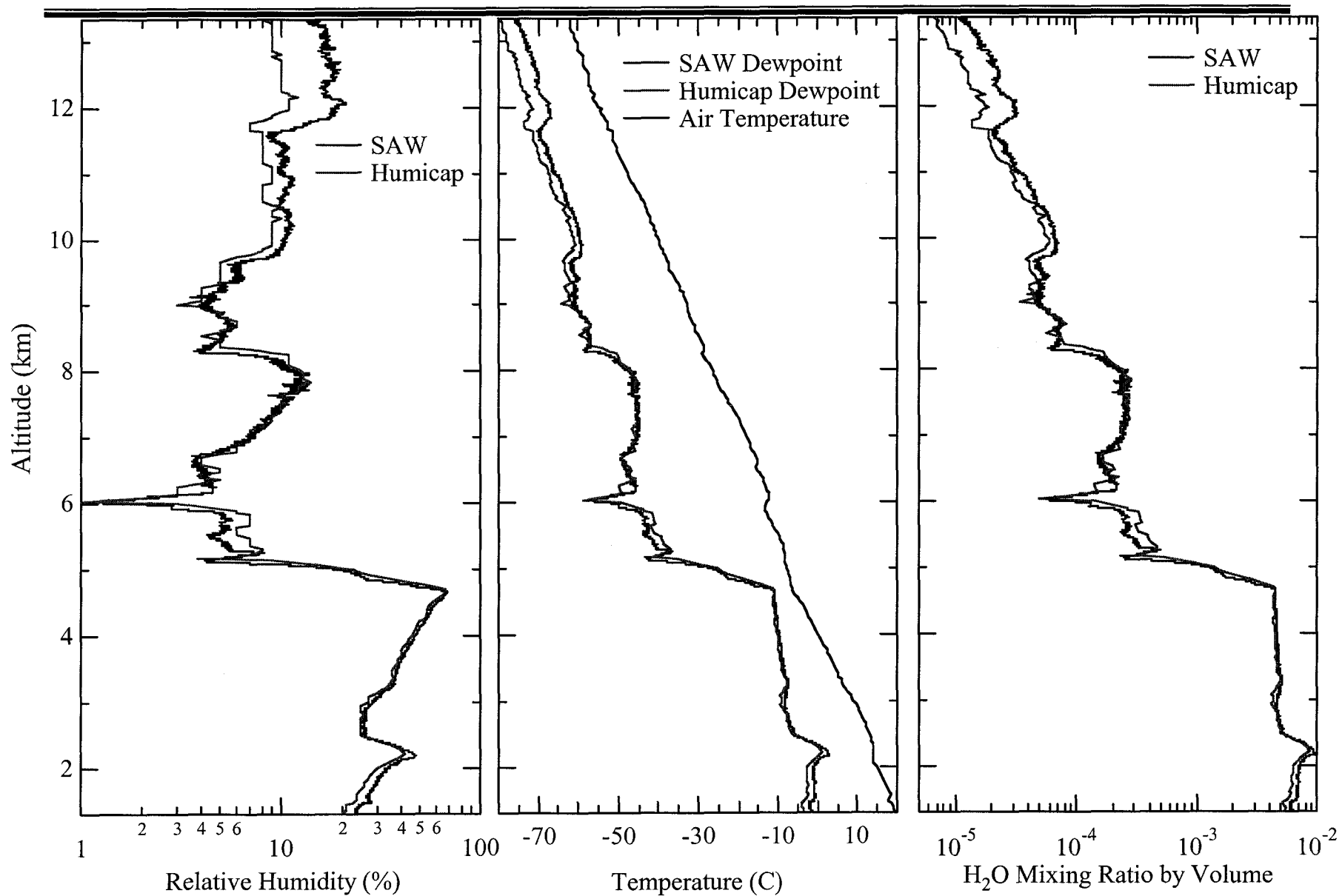
## Flight Test of JPL Radiosonde



- Flight validation of JPL radiosonde with miniaturized SAW hygrometer.
- Direct *in situ* comparison with Vaisala radiosonde relative humidity sensor.
- Extremely low frostpoint:  $-76^{\circ}\text{C}$  at 44000 feet (6 ppm)
- GPS tracking and payload recovery

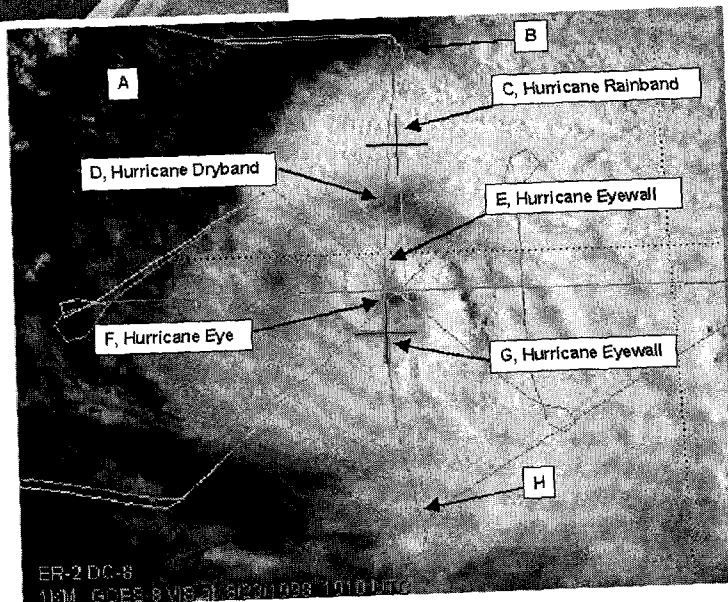
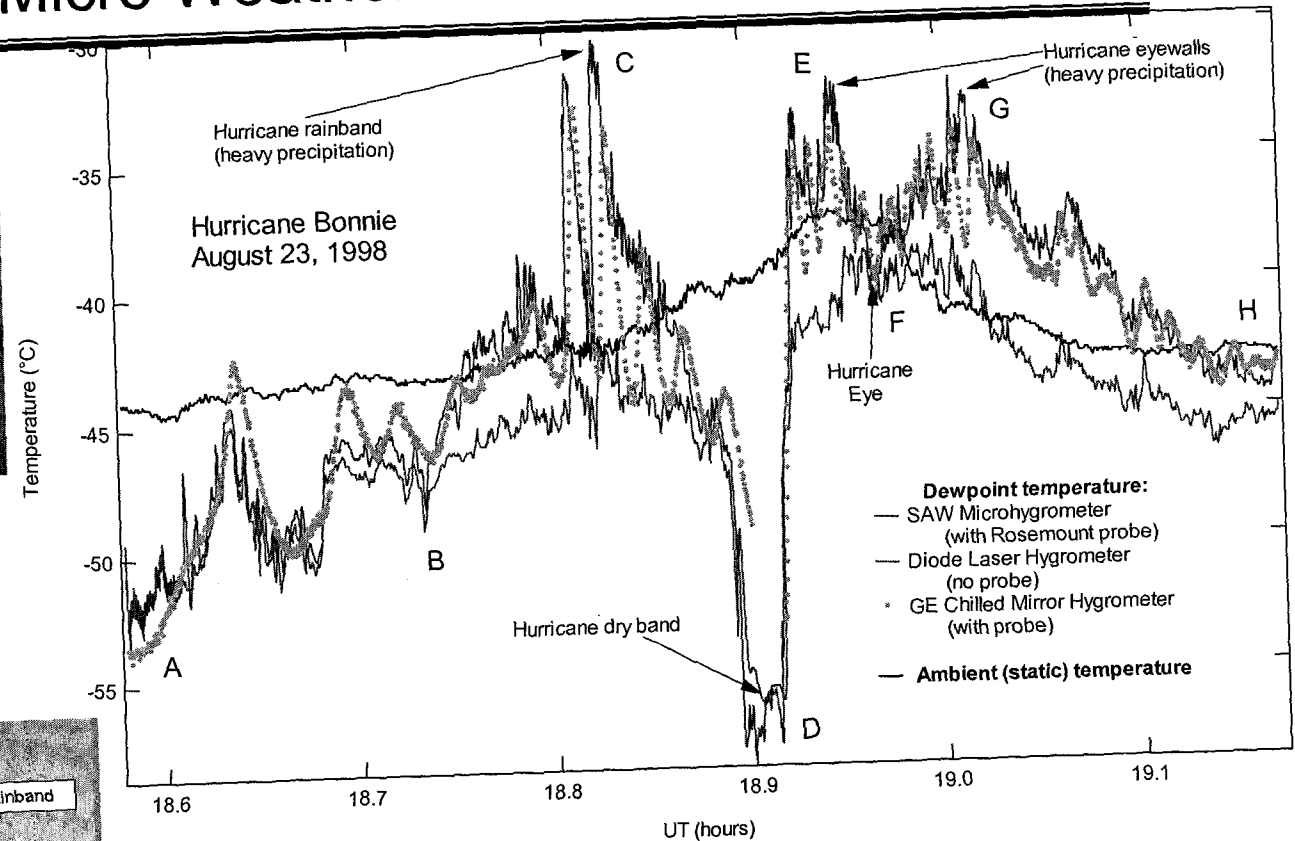
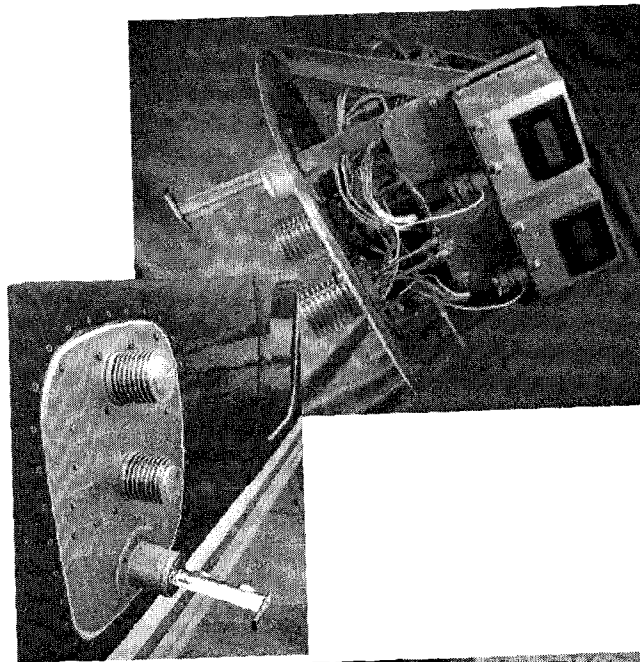


## Comparison of SAW Hygrometer with Humicap





## Micro Weather Station



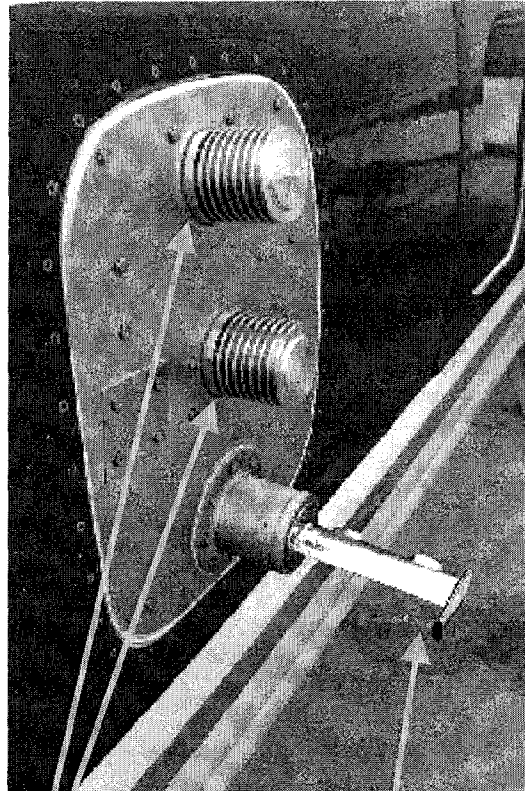
**NASA's Third Convection and Moisture Experiment**  
**In situ humidity measurements with dewpoint microhygrometer**



## CAMEX-3 Hurricane Mission - Experimental setup



### DC-8 window assembly



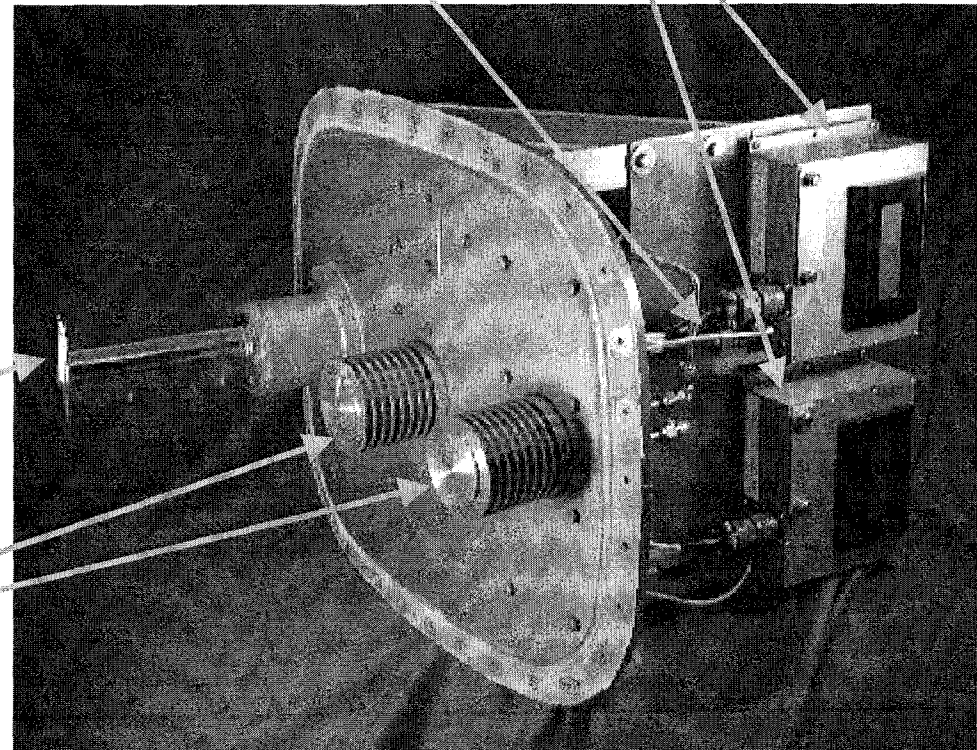
### Electronics include

- Instrument controller
- Flash card data logger

### Monitoring

- LCD display shows current measurements and status
- Laptop computer for remote monitoring and control

### Stainless-steel tubing for air sampling

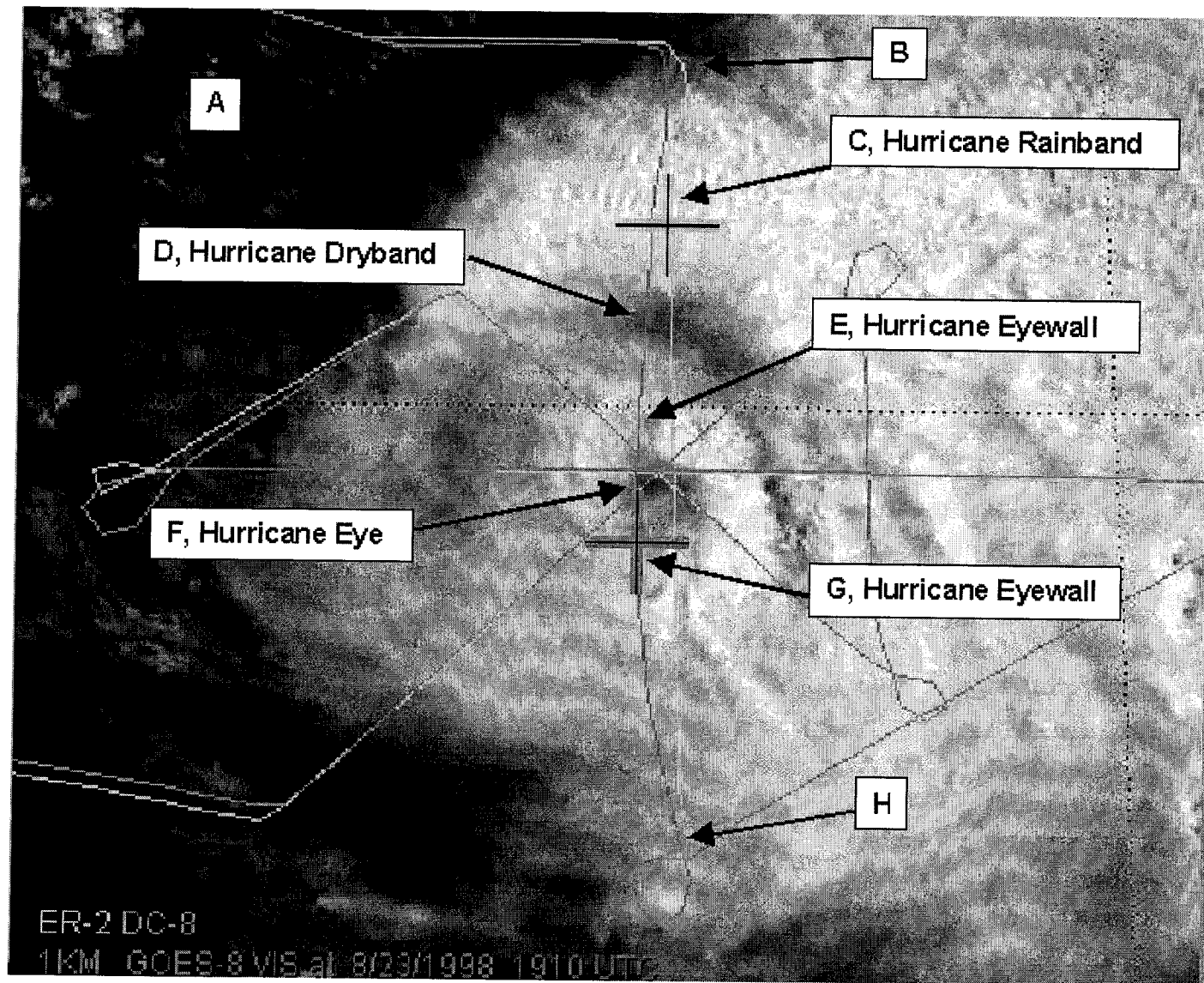


### Air-sampling probe

### Air-cooled housings containing each one SAW device

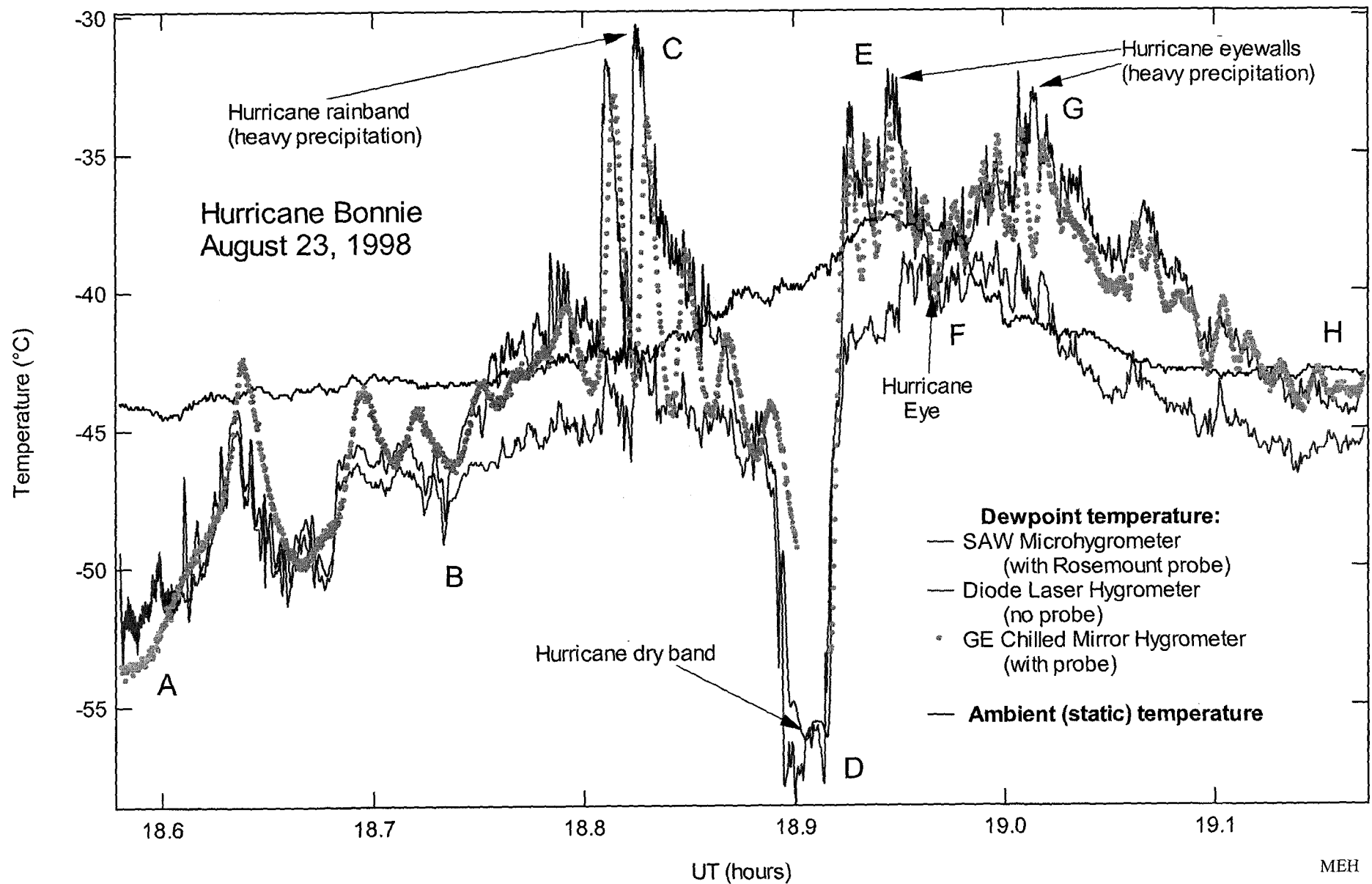


## CAMEX-3 - Hurricane Bonnie (08/23/98)



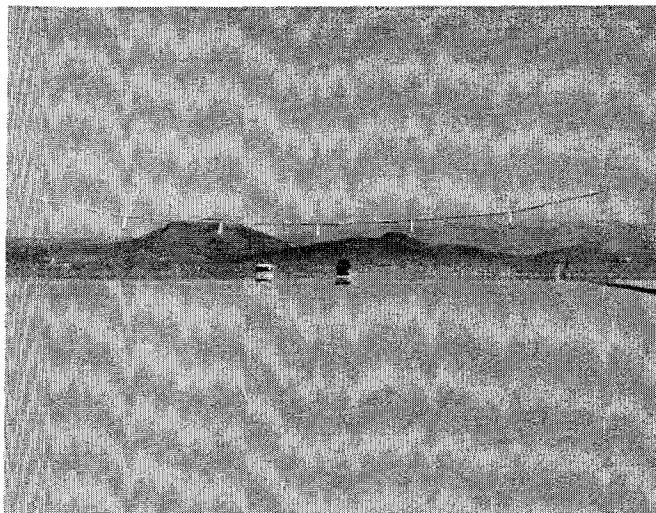


## CAMEX-3 - Dewpoint Measurements





# Helios UAV



Dryden Flight Research Center EC99-45285-7 Photographed DEC1999  
Trailed by support vehicles, the prototype of the Helios solar-electric flying wing  
lands on Rogers Dry Lake to conclude its sixth flight. NASA Dryden/Tom Tschida

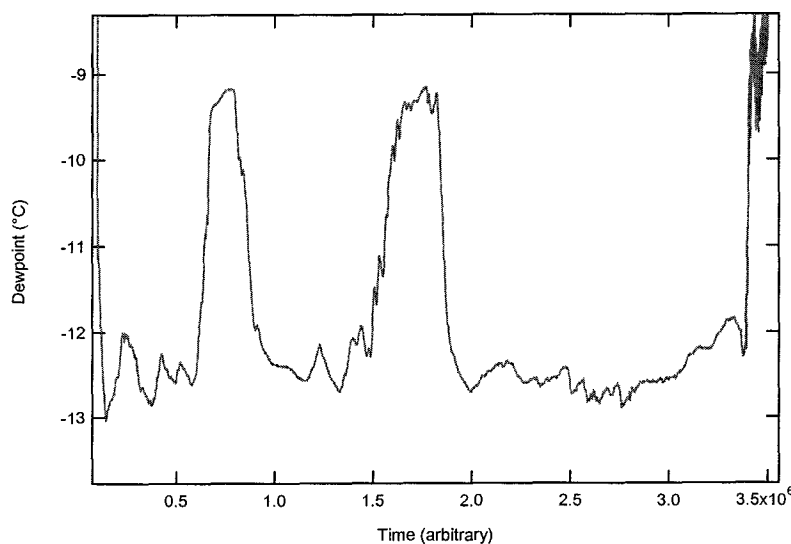
## AeroVironment Helios UAV

Unpiloted aircraft designed for high-altitude (100,000 ft),  
long-term deployment (6 months)



Dryden Flight Research Center EC99-45140-11 Photographed 18 AUG 1999  
Prototype of Helios solar-electric high-altitude flying wing.  
NASA/Dryden Tom Tschida

**SAW  
Hygrometer  
dewpoint  
during  
Helios flight  
on Oct 13,  
1999.**



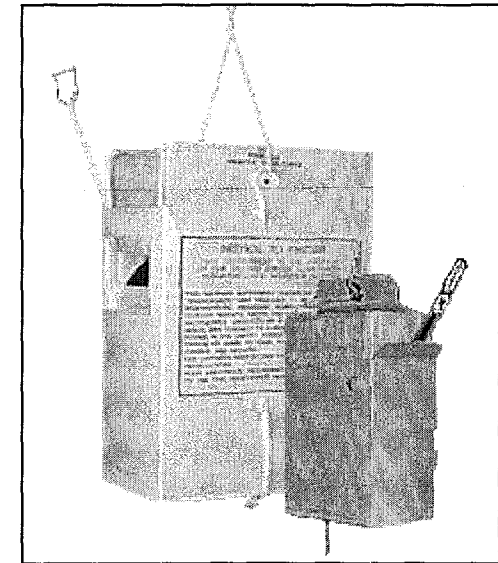


# The JPL SAW Microhygrometer



## Potential Applications

- NASA
  - Space station ( $H_2O$  as a tracer of  $CO_2$ )
  - Earth science
  - Planetary science?
- NWS/NOAA
  - Radiosondes
  - Weather monitoring
  - NOAA Radiosonde Replacement Program
  - <http://www.rrs.nws.noaa.gov/>
- Laboratory reference standards
- Lab / Handheld instrumentation
- Industrial process control
- Military:
  - Battlefield sensor packages
  - Radiosondes
  - Environmental monitoring
  - Munitions storage*



Balloon-borne radiosondes used by the National Weather Service. The NWS launches 80,000 radiosondes each year.



## The JPL SAW Microhygrometer

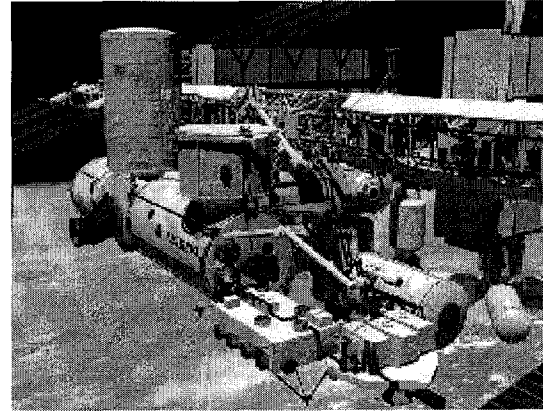


### Conclusions:

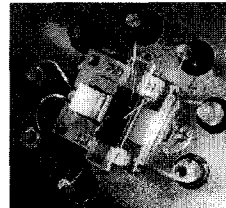
- *Better* - faster, smaller - than commercial state-of-the-art
- Large development effort invested
- Good potential for commercialization



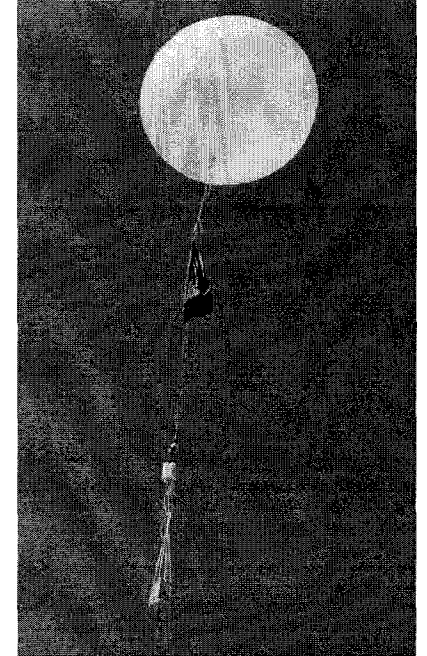
Unmanned Aeronautical Vehicles  
(AeroVironment Helios)



Space Station



Reference  
Radiosonde



NASA DC-8 (CAMEX-4, Crystal)

